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Setup for characterising the spectral responsivity of Fabry-Perot-interferometer-based hyperspectral cameras

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1. Introduction

Hyperspectral cameras capture the spectrum of the objects in the imaged view via dozens of narrow-band spectral channels of the camera. Knowledge of the spectral responsivity of the channels is essential when interpreting the acquired hyperspectral data and assessing its reliability. The spectral responsivity of the camera channels may vary within the image area. This paper presents a measurement setup and data analysis routine for characterising the spectral responsivity of a hyperspectral camera. This method was used to characterise the spectral responsivity of a Fabry–Pérot-interferometer-based hyperspectral camera. The characterisation method implemented in this study was able to reveal several channel leaks in the measured wavelength range. In the image area there is an approximately 1.5 nm shift in the channel wavelengths, and up to 10% variation in the channel bandwidths. The expanded uncertainties ($k = 2$) for the measured channel bandwidths, sensitivities and wavelengths were 7.9%, 9.5% and 0.64 nm, respectively.

Keywords: hyperspectral imaging, spectral responsivity, camera calibration, Fabry–Pérot-interferometer

(Some figures may appear in colour only in the online journal)
channels are determined both as a function of wavelength and as a function of image pixel coordinates. The presented method is independent of the inner architecture of the camera under study, and can be generalised to most hyperspectral cameras.

2. Methods and materials

2.1. Spectral responsivity

The basic principle of the characterisation measurements is to sequentially image wavelength-adjustable, narrow-band radiation source with the camera under study. This is an established method for characterising the spectral responsitivity of devices that measure optical radiation [8–10], including hyperspectral cameras [11–14].

Another method for measuring the spectral sensitivities of the channels is to simply image a broadband radiation source with a known spectrum. The broadband method is simpler and faster, but requires prior knowledge of the wavelength centroids of the channels, and of the sensitivities and wavelengths of possible channel leaks. Incomplete or inaccurate characterisation of these features will lead to distortions in the measured channel sensitivities.

In this study, the spectral responsivities of the channels are determined in relative scale. With the relative responsivities and leaks characterised, the absolute scale can then be determined by imaging a broadband source with a known spectrum.

2.2. Camera under test

The camera under test is a spectral scanning device, and utilises a piezoelectrically actuated Fabry–Pérot-interferometer for spectral filtering. A prototype camera based on this technology in described in [15–18]. The spectral range of the camera is from 490 nm to 910 nm, with the incoming radiation split onto two separate detectors, one being active from 490 nm to 640 nm and the other from 640 nm to 910 nm. The bandwidths of the spectral channels vary from 5 nm to 17 nm. The pixel resolution is 1010 × 1010 pixels, and field of view is 36.5° × 36.5°. The focal length of the camera is 9 mm, and the camera has fixed optics, meaning that there are no focusing options. The spectral data are saved using a 12-bit depth for each channel. The spectral channels of the camera are configurable, but not completely unconstrained, as only certain wavelength and channel bandwidth combinations are allowed by the device.

2.3. Measurement setup

The overview of the measurement setup is shown in figure 1. The radiation source of the system was a laser-driven plasma light source, with wavelength range of 170–1000 nm. The beam of the source was focused on the entrance slit of the monochromator using two off-axis parabolic mirrors. The monochromator had a single grating and a focal length of 750 mm. The monochromator entrance and exit slit widths were fixed to keep the output bandwidth of the monochromator at 1 nm on average. To eliminate higher order diffractions in the monochromator output, an external filter wheel equipped with three order-sorting filters with cutoff wavelengths of 280 nm, 455 nm and 830 nm was placed after the monochromator exit slit. The wheel was also equipped with a shutter for taking dark reference pictures.

A 1-mm-thick piece of white polytetrafluoroethylene (PTFE) was placed after the filter wheel to act as a transmitting diffuser. The distance between the camera and the diffuser was 175 mm. To prevent stray light from affecting the images, the camera and the irradiated diffuser were encased in a black cabinet. The irradiated surface covered only a portion of the field of view of the camera, so the camera had to be turned in order to cover the whole field of view. This was achieved by mounting the camera on a motorised turntable.

The spectral irradiance of the monochromatic source depends on the spectral power distribution of the radiation source, spectral throughput of the monochromator, spectral transmittance of the filters and spectral transmittance of the diffuser. The spectral irradiance of the system without the diffuser was measured with a pyroelectric radiometer. The spectral transmittance of the diffuser plate was measured separately with a scanning spectrophotometer. The combined setup radiation was calculated as the product of the measured spectral irradiance and diffuser transmittance values. The resulting spectral radiance of the source is shown in figure 2.

The wavelength scale and output bandwidth of the monochromator were calibrated by measuring the monochromator output with a spectroradiometer. The output bandwidth of the monochromator changed linearly from 1.05 nm to 0.87 nm in the wavelength range from 500 nm to 900 nm.
2.4. Measurement sequence

To account for the change in dark signal levels, sequences of dark frames were measured at regular intervals. When analysing the measurement data, the dark signal for each measurement was obtained by linear interpolation of the average signals from the previous and the next dark sequence. To reduce the impact of random noise in the measurements, three images were taken for each measured wavelength. After subtracting the dark signal, these images were averaged to form a single measurement image at the given wavelength. The exposure time of the camera was kept at 500 ms per channel, which was a compromise between measurement noise and measurement time.

The relative spectral responsivities of 46 channels were measured in the wavelength range from 470 nm to 930 nm with a 0.5 nm sampling interval. The irradiated area was kept at the centre of the image. The total amount of images taken was 2763 (921 × 3) and the amount of dark frames was 399. Measuring the channel properties across the whole spatial area with same spectral resolution would have taken hundreds of hours and produced several terabytes of data, so for the spatial analysis, a set of 12 channels were measured for 162 different wavelengths at 37 spatial locations spanning the image area, resulting in a total of 17 982 (37 × 162 × 3) images and 918 dark frames. The twelve channels covered four camera channel wavelengths with three different bandwidth configurations.

2.5. Data analysis

The irradiated area covered an approximately 30 × 30 pixel area in the image plane. The irradiated areas at different image locations were automatically detected from the images via filtering and thresholding. Each area was averaged to a single measurement point at the centre of the area. This averaging mitigated the effects of the possible spatial non-uniformities of the irradiated area. To account for the spectral non-uniformity of the radiance of the monochromatic source, the obtained spectral responsivities were normalised by the combined setup spectral radiance, shown in figure 2. The distortion caused by the spectral bandwidth of the source was corrected with Lucy–Richardson deconvolution algorithm [19, 20], with the change in the monochromator bandwidth in the measured wavelength range taken into account.

Wavelength, spectral bandwidth and spectral sensitivity were determined for each channel. The channel wavelengths were calculated as centroids of the spectral responsivity, channel bandwidths as full width at half maximum (FWHM) and channel sensitivities as trapezoidally integrated spectral responsivities. To avoid including leaks in the calculations,
the centroid and area calculations were limited to a wavelength range of 50 nm centered at the wavelength of the maximum responsivity of the channel. The wavelength difference between the responsivity maximum and the calculated centroid was 0.3 nm on average.

3. Camera characterisation results

3.1. Spectral responsivity

The relative spectral responsivities measured for the set of 46 channels are shown in figure 3. The irregularities in the spectral responsivities measured on wavelengths longer than 800 nm are likely caused by the high-intensity peaks in the spectrum of the radiance source (see figure 2). Additionally, the unidealities of the channels around 640 nm are likely related to the sensor change at 640 nm. 15 of the studied 46 channels had regions of sensitivity outside the main channel. Some of these leaks are illustrated in figure 4.

The results of the spatial scanning measurements were calculated separately for the 12 channels measured. Figure 5 illustrates the channel wavelength shift in the image area. The shift is up to 1.5 nm from the centre towards image edges. A similar effect, called Smile [21], exists for diffraction-based hyperspectral cameras. The Smile effect of the diffraction cameras is caused by optical distortions in the incoming light [21].

Figure 6 shows the bandwidth variation in the image area. The bandwidths of the studied channels change by up to 10% across image area. The changes appear random, and while channels located close to each other in the wavelength scale show some seemingly similar patterns, they are too vague to draw any definitive conclusions. Nevertheless, even if mathematical modelling of the bandwidth variations is unviable, the pattern and magnitude of the changes can be determined with characterisation measurements.

3.2. Uncertainty analysis

The measurement uncertainties were determined separately for the channel sensitivities, wavelengths and bandwidths, and separately for short and long wavelengths, in ranges from 470 nm to 800 nm and from 800 nm to 930 nm. To determine the repeatability of the measurements, a measurement series for seven channels was repeated ten times. Three of the channels were in the long wavelength region and four in the short wavelength region. The main source of uncertainty was the low signal level of the radiance source, which is seen as limited repeatability of the results.
The validation results for the measured channel sensitivities were validated by measuring an integrating-sphere-based radiance source with the characterised camera and a spectroradiometer for a reference. Altogether 16 images were taken, six of which were dark frames. After dark reference removal the images were averaged. The opening of the integrating sphere covered an approximately $50 \times 50$ pixel area at the centre of the image. The relative spectral radiance was calculated from the average of the pixel values of the illuminated area. The validation results for the measured correction, factory calibration and uncorrected raw data are shown in figure 7. The deviation between the spectrum measured with the camera and the spectrum measured with the spectroradiometer was calculated as the root mean square error (RMSE) of the relative differences. For comparison, the offsets of the relative spectral power distributions were adjusted so that the RMSE criterion was minimised.

The normalised RMSE of the corrected spectral power distribution was 3.6%. For comparison, the raw data RMSE was 21.3% and the manufacturer calibration RMSE was 9.5%. Figure 8 shows the relative difference between the measurement points and the reference spectrum together with the standard and expanded uncertainties. The channel at 505 nm was deemed an outlier and ignored in the RMSE calculation and normalisation. The channel had a significant leak at 644 nm (see figure 4(a)), which received a much higher signal than the main channel, resulting in the large error.

### Table 1. Uncertainty budget for the measured channel sensitivities.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>470–800 nm</th>
<th>800–930 nm</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyroelectric radiometer spectral responsivity</td>
<td>1.0</td>
<td>1.0</td>
<td>B</td>
</tr>
<tr>
<td>Reference irradiance measurement repeatability</td>
<td>2.3</td>
<td>4.4</td>
<td>A</td>
</tr>
<tr>
<td>Source signal level drift</td>
<td>1.5</td>
<td>1.5</td>
<td>A</td>
</tr>
<tr>
<td>Diffuser transmittance measurement repeatability</td>
<td>2.2</td>
<td>2.8</td>
<td>A</td>
</tr>
<tr>
<td>Camera measurement repeatability</td>
<td>2.0</td>
<td>2.9</td>
<td>A</td>
</tr>
<tr>
<td>Combined standard uncertainty ($k = 1$)</td>
<td>4.2</td>
<td>6.2</td>
<td></td>
</tr>
<tr>
<td>Expanded uncertainty ($k = 2$)</td>
<td>8.3</td>
<td>12.5</td>
<td></td>
</tr>
</tbody>
</table>

### Table 2. Uncertainty budget for the measured channel centroid wavelengths.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>470–800 nm</th>
<th>800–930 nm</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength calibration uncertainty</td>
<td>0.1</td>
<td>0.1</td>
<td>B</td>
</tr>
<tr>
<td>Monochromator wavelength accuracy</td>
<td>0.05</td>
<td>0.05</td>
<td>B</td>
</tr>
<tr>
<td>Camera measurement repeatability</td>
<td>0.3</td>
<td>0.3</td>
<td>A</td>
</tr>
<tr>
<td>Combined standard uncertainty ($k = 1$)</td>
<td>0.32</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td>Expanded uncertainty ($k = 2$)</td>
<td>0.64</td>
<td>0.64</td>
<td></td>
</tr>
</tbody>
</table>

### Figure 7. Relative spectral radiance of an incandescent reference source measured using the hyperspectral camera and a spectroradiometer as a reference.

### Figure 8. Uncertainties and relative errors in the measured spectrum with the measured correction of this work.

3.3. Validation of the results

The obtained spectral sensitivities were validated by measuring an integrating-sphere-based radiance source with the characterised camera and a spectroradiometer for a reference. Altogether 16 images were taken, six of which were dark frames. After dark reference removal the images were averaged. The opening of the integrating sphere covered an approximately $50 \times 50$ pixel area at the centre of the image. The relative spectral radiance was calculated from the average of the pixel values of the illuminated area. The validation results for the measured correction, factory calibration and uncorrected raw data are shown in figure 7. The deviation between the spectrum measured with the camera and the spectrum measured with the spectroradiometer was calculated as the root mean square error (RMSE) of the relative differences. For comparison, the offsets of the relative spectral power distributions were adjusted so that the RMSE criterion was minimised.

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4. Conclusion

This paper presents a measurement setup and analysis for characterising the spectral responsivity of hyperspectral cameras. The core of the setup was a tunable monochromatic irradiance source, which was used to irradiate a transmitting diffuser. The camera under study was mounted on a motorised turntable, sequentially imaging the diffuse surface at different wavelengths and different viewing angles. The spectral responsivities of the channels were extracted from the pixel values of the images.

The camera under study was a Fabry–Pérot-interferometer-based spectral scanning camera. The relative spectral responsivities of its channels were determined both as a function of wavelength and as a function of image location. The results revealed several channel leaks, or regions of sensitivity outside the main channels. In the spatial image area there was an up to 1.5 nm shift in the channel wavelength from the image centre towards image corners. The measured channel bandwidths varied by up to 10% across the image area. The expanded uncertainty \(k = 2\) for the measured channel sensitivities is 9.5%, for the channel bandwidths 7.9% and for the channel wavelengths 0.64 nm.

The measurements were affected by the poor signal-to-noise ratio, due to the low signal level of the utilised radiation source. For future research, choosing a radiation source with higher signal output, as well as adding a monitor detector would decrease the uncertainty of the measurements. Nevertheless, the achieved results confirm the viability of the presented setup for hyperspectral camera calibrations. Based on this study, a more advanced calibration facility will be implemented at the Metrology Research Institute.

Acknowledgments

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References